

## Whole-Spacecraft Vibration Isolation Flown on the Minotaur Launch Vehicle

Paul S. Wilke,

CSA Engineering, Inc., 2565 Leghorn St, Mountain View, CA 94043, 650-210-9000 wilke@csaengineering.com

Conor D. Johnson

CSA Engineering, Inc., 2565 Leghorn St, Mountain View, CA 94043, 650-210-9000 cjohnson@csaengineering.com

Kenneth R. Darling

Orbital Sciences Corp., 3380 South Price Rd, Chandler, AZ 85248, 480-814-6830 darling.ken@orbital-lsg.com

**Abstract.** Small launch vehicles present an economically viable method for placing small satellites into orbit. These launch vehicles would be even more attractive to satellite customers if they could provide a softer ride to orbit. Passive whole-spacecraft vibration isolation systems have been developed for small launch vehicles to greatly reduce the dynamic launch loads. To date, two types of isolation systems have been designed. The first is a single-axis “SoftRide” axial isolation system that provides isolation for predominantly axial loads. This type of system has been flown successfully three times on the Taurus/GFO mission in February 1998, the Taurus/STEX mission in October 1998, and the Taurus/MTI mission in March 2000. The second type of isolation system is a multi-axis device that provides vibration isolation in three axes. This type of system is needed to alleviate dynamic launch loads on the Minotaur vehicle (Figure 1). This multi-axis “SoftRide” system inserts flexibility and damping in three orthogonal axes between the launch vehicle and the satellite. The result is that dynamic launch loads with both axial and lateral components can be effectively mitigated. Additionally, these isolation systems provide extreme reductions to shock and structure-borne acoustic loads. The multi-axis isolation system is a logical extension of the single-axis system and has the same qualities of being simple, passive, small, lightweight, reliable, and highly effective. Two flights have demonstrated this new isolation system to date: these are the Minotaur/JAWSAT mission in January of 2000 and the Minotaur/MightySat mission in July 2000. Coupled loads analyses and flight telemetry data indicate that the new multi-axis vibration isolation system performed as expected and greatly reduced dynamic launch loads for the satellites. This new isolation system can be sized for any satellite and is being considered for other small and large launch vehicle missions.



Figure 1 Minotaur

### Introduction

The OSP Space Launch Vehicle (SLV), also known as the OSP Minotaur launch vehicle, was developed under the Orbital Suborbital Program (OSP) awarded to Orbital Sciences Corporation (Orbital) in September 1997 by the U.S. Air Force. The goal of the orbital part of the OSP program is to develop and field Minuteman II derived space launch vehicles in support of US Government activities. The Air Force contracted with Orbital Sciences Corporation to integrate the surplus Minuteman II rocket motors with other system elements, integrate the launch vehicle with the payload and launch facilities, and execute the launch mission (Reference 1).

The OSP Minotaur is a four stage, ground launched solid propellant, inertially guided spacelift vehicle. It uses the first two stages from the Minuteman II intercontinental ballistic missile (ICBM) combined with the upper two stages, structure, and fairing from the Pegasus XL air-launched space vehicle. The OSP Minotaur approach reduces the development and recurring launch costs by this utilization of the commercially developed, flight proven components and propulsion from the Pegasus vehicle (Reference 1).

The overall OSP Minotaur vehicle configuration consists of two major subassemblies: 1) the Lower

Stages Assembly (LSA) consisting of the Minuteman boosters and 2) the Upper Stages Assembly (USA) incorporating the Pegasus-derived front section and new interstage between the LSA and the Pegasus motors. The vehicle length is approximately 63 ft from Stage 1 nozzle exit planes to the top of the fairing. The launch weight of the OSP Minotaur is approximately 80,000 lb, not including the mass of the payload (Reference 1).

The vehicle utilizes surplus Minuteman II M55A1 and SR19 solid rocket motors for Stages 1 and 2 respectively. These motors are refurbished by the USAF and provided as GFE. Stages 3 and 4 consist of Orion 50XL and Orion 38 motors, respectively, manufactured by Alliant TechSystems. These motors are virtually identical to the Pegasus XL Stage 2 and Stage 3 motors. The payload fairing is the 50 in diameter Pegasus design with some minor changes (Reference 1).

The maiden launch of the OSP Minotaur occurred on January 26, 2000. This vehicle carried a suite of 5 payloads, dubbed “JAWSAT”, into the proper orbit. The second launch of the vehicle with the MightySat II.1 spacecraft took place on July 19, 2000 (Figure 2). This vehicle also placed the spacecraft into its desired orbit. The respective payload customers considered both missions to be very successful.

The OSP Minotaur vehicle is an ideal launcher for small satellites because of its ability to accommodate different satellite configurations or multiple satellites on a single mission, and to operate from multiple launch sites on either coast.

During ascent to orbit, all launch vehicles go through a series of events such as motor ignitions, stage separations, motor burns, etc. that result in various types of dynamic loads at the interface to the spacecraft. Vibration isolation, also referred to as a SoftRide system, placed between the launch vehicle and the spacecraft, can attenuate the magnitudes of these loads to the spacecraft. In some cases this makes it possible to fly a spacecraft in an otherwise excessive launch environment and in other cases the isolation system

simply provides additional margin to insure that the spacecraft arrives in orbit unharmed.

The Minotaur launch vehicle has proved to be a good test bed to demonstrate the capabilities and performance of the new multi-axis “SoftRide” whole-spacecraft vibration isolation system.

Both of the OSP Minotaur flights to date included the SoftRide “MultiFlex” vibration isolation system to reduce spacecraft responses to induced loads and reduce environments transmitted between the launch vehicle and spacecraft.



Figure 2 Launch of Minotaur

### Vibration Isolation Design Methodology

The design of classical vibration isolation systems typically assumes that the base is rigid and the isolated payload has dynamics only well above the isolation frequency. Contrary to this, the design of a SoftRide system for whole-spacecraft isolation must be done with full knowledge that the structures on either side of the isolation system, namely the launch vehicle and the

spacecraft, are both very rich in dynamics. This necessitates that the SoftRide system must be approached from the perspective of system-level dynamics.

Some of the typical design constraints are weight, volume, and strength. Two other major constraints on the design of the isolation systems are:

- Do not introduce modes that are too low in frequency or high in amplitude such that they interfere with the LV control system.
- Do not introduce excessive spacecraft to fairing relative displacement.

The design of the isolation system therefore requires coupled-loads analysis (CLA), along with detailed design analysis. The basic procedure (Figure 3) involves the following steps:

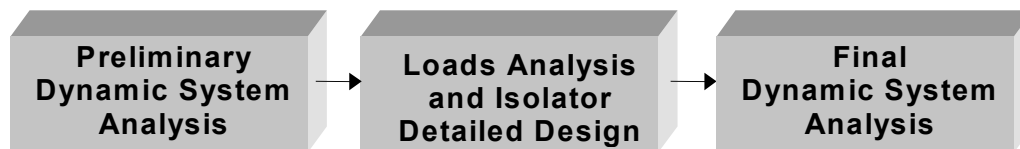


Figure 3 SoftRide design methodology

The CLA must be performed with actual launch vehicle and spacecraft models. The typical procedure at CSA is to obtain LV models and loads for worst case conditions from the LV manufacturer and perform a “mini” CLA with the latest model of the spacecraft

- Perform a preliminary “mini” CLA using only the worst load cases to optimize system-level isolator performance and get isolator component-level requirements
- Calculate maximum isolator loads for isolator strength design; size isolator to meet stiffness, damping, strength, and other requirements
- Perform a final “full” CLA using detailed isolator models in the system model to verify system-level performance

supplied by its manufacturer. Once the detailed isolator design analysis is completed, then a model of the isolators is delivered to the LV manufacturer for a complete and final CLA.

## Multi-Axis Vibration Isolation

### Background

Different launch vehicles with their unique environments need different types of isolation systems. There are three categories of passive whole-spacecraft vibration isolation systems:

1. Isolators with only axial (thrust direction) compliance
2. Isolators with only lateral compliance
3. Isolators with combined axial and lateral compliance

Preliminary system-level coupled loads analyses showed that the spacecraft on Minotaur benefit the most from the third category of isolator having combined axial and lateral compliance.

A hardware concept, called the SoftRide MultiFlex (Figure 4) was developed and flown on the first and second flights of the Minotaur launch vehicle. The MultiFlex whole-spacecraft isolation system is made up of a series of isolator elements inserted in the field joint between the launch vehicle and the spacecraft as shown in Figure 5.

The MultiFlex system has the following attributes:

- Provides large reductions in most spacecraft responses to the worst-case loads
- Meets all design constraints
- Low weight =26 lb
- Small size (spacecraft moved forward 4 inches)
- Mounted to existing LV field joint
- Does not require any changes to existing flight hardware
- No linkages, fluids, or nonlinearities



Figure 4 SoftRide MultiFlex

Coupled loads analyses for both Minotaur missions, JAWSAT and MightySat, showed that the SoftRide MultiFlex isolation system greatly reduced dynamic responses on the spacecraft. This is illustrated in the transient responses shown in Figure 6 and Figure 7.



Figure 5 Typical installation of SoftRide MultiFlex

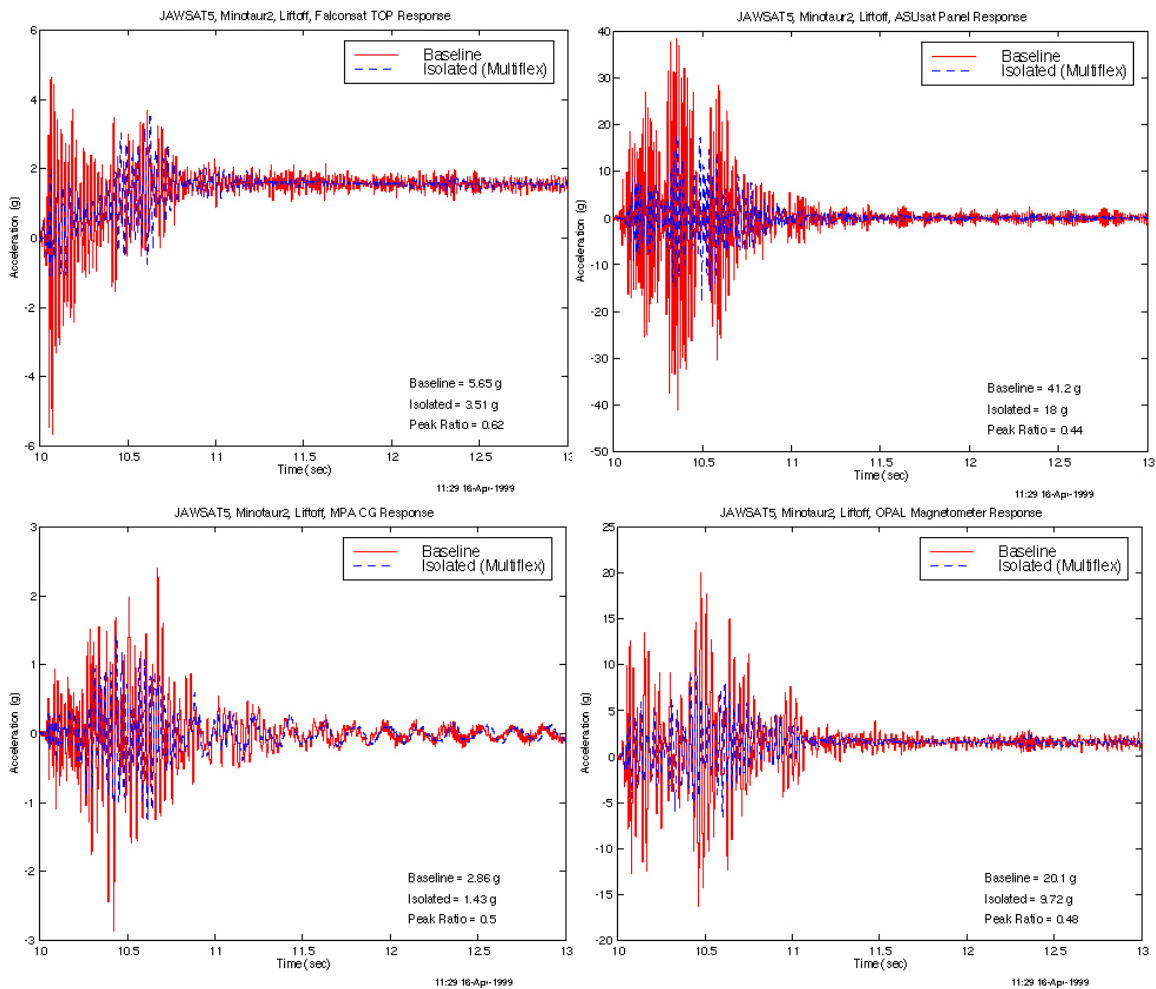


Figure 6 Representative response reductions for JAWSAT due to the SoftRide system

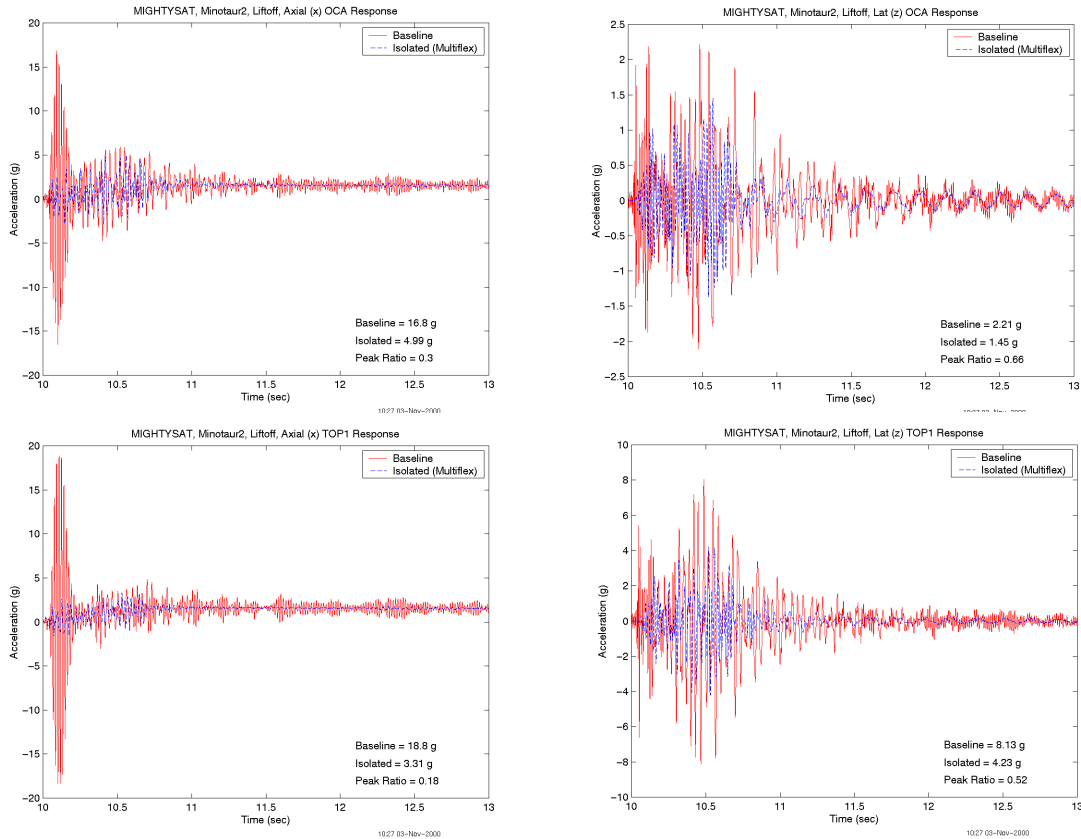


Figure 7 Representative response reductions for MightySat due to the SoftRide system

### Component Testing

Extensive component-level testing was performed on the SoftRide MultiFlex isolation system. These tests were done for the purposes of qualification and acceptance of the isolation system for flight. Component-level tests included:

- Static loads
- Complex stiffness (stiffness and loss factor)
- Random endurance
- Sine endurance

Axial isolator stiffness and loss as a function of temperature is shown in Figure 8. The repeatability or consistent behavior of the isolators is illustrated by plotting the complex stiffness of all 64 flight units (Figure 9). All of the isolators fall within a  $\pm 3\%$  band on the stiffness curve. This scatter is due to machining tolerances and also to slight temperature variations.

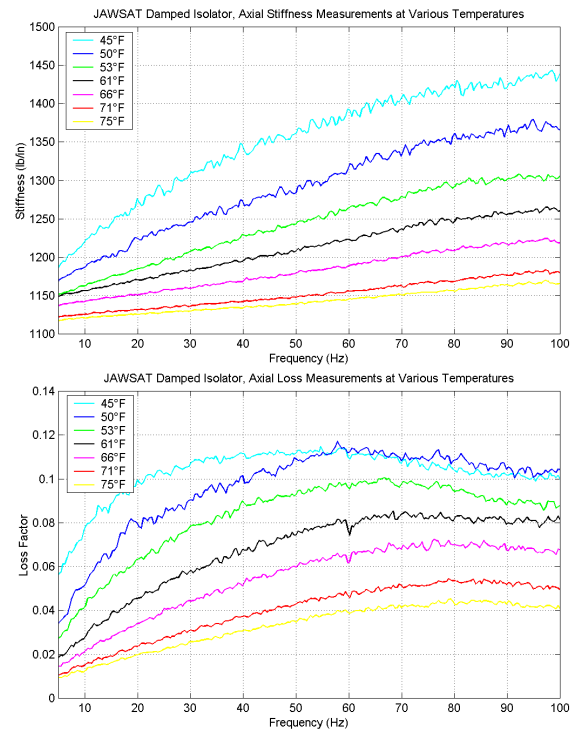


Figure 8 Isolator axial stiffness and loss factor as a function of temperature

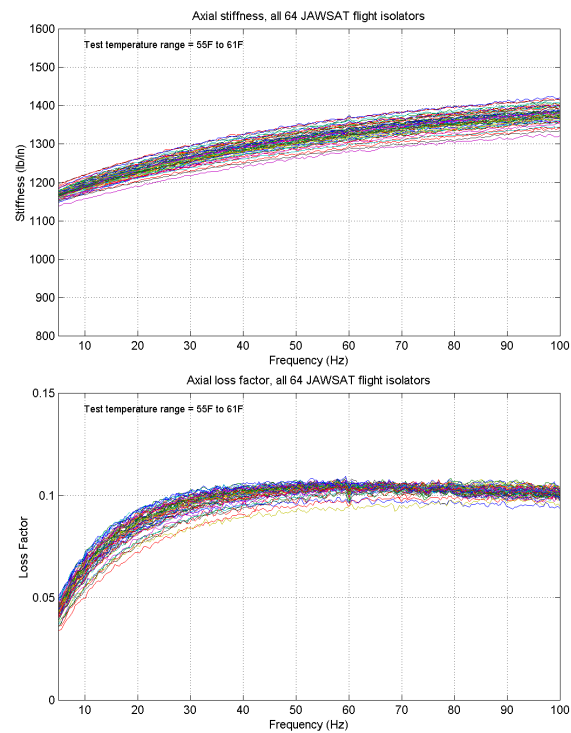


Figure 9 Overlay plot of axial stiffness & loss factor results for all flight isolators



## Flight Heritage

SoftRide MultiFlex whole-spacecraft vibration isolation systems have been designed, fabricated, tested, and flown for the explicit purpose of attenuating transient dynamic launch vibrations. To date, two of these systems have been flown on Orbital's Minotaur launch vehicles, the first in January 2000 with the JAWSAT spacecraft and the second in July 2000 with the

MightySat spacecraft. A review of flight data from the JAWSAT flight has shown significant reduction not only in transient vibration but also in random vibration and shock. The following is a presentation of the flight data pertaining to the performance of the SoftRide system for the JAWSAT flight; no data specific to the SoftRide system was acquired for the MightySat flight.

### Minotaur/JAWSAT Mission

The Air Force funded a significant data acquisition system for the purpose of assessing the performance of the SoftRide vibration isolation system. A total of 18 accelerometers were flown for measuring accelerations on both the "hard" side (launch vehicle side) and "soft" side (spacecraft side) of the isolation system. These accelerometers were arranged into 6 triaxial sets: three triaxial sets on the hard side and three triaxial sets on the soft side.

Flight data was examined and the trends observed agreed very well with the predictions of coupled loads analyses. An example of some SoftRide acceleration flight data from the JAWSAT mission is shown in Figure 10. Note that excellent vibration isolation was achieved in both the axial (thrust) and the lateral directions.

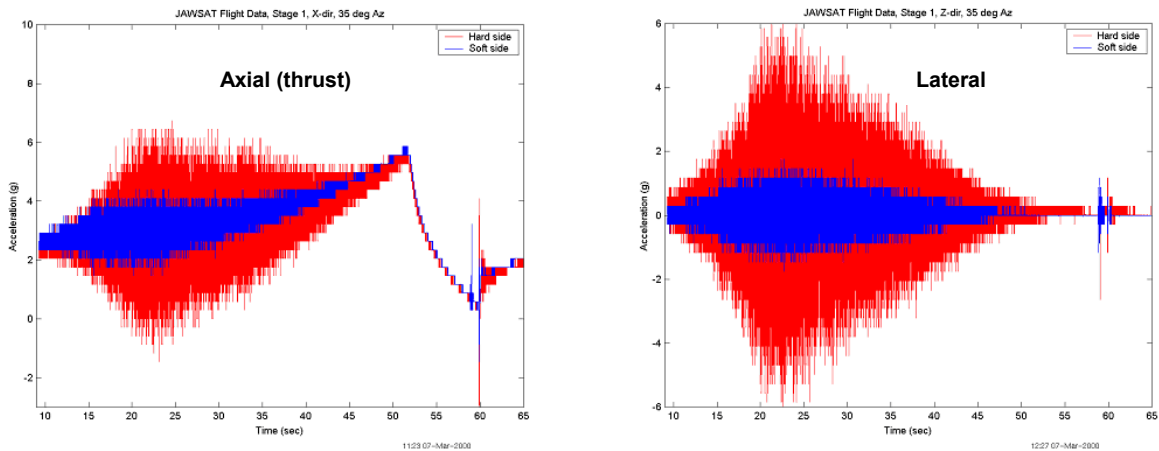


Figure 10 Typical SoftRide flight data from the Minotaur/JAWSAT mission

### Shock Attenuation

The JAWSAT SoftRide isolation system was tested, at the component level, for its ability to withstand shock inputs. A shock simulating a flight event such as a stage or fairing separation was input to the base of the SoftRide system and the isolated response was measured. The results of these tests showed that not only did the system survive the largest shock input, but also it gave excellent shock attenuation above 50 Hz (Figure 11).

Data showing the fairing separation shock event from the Minotaur/JAWSAT flight is shown in Figure 12. The flight accelerometers were not shock accelerometers and therefore some clipping of the high-level "hard side" shocks has occurred. However, the isolated "soft side" shows greatly reduced shock inputs to the base of the spacecraft.

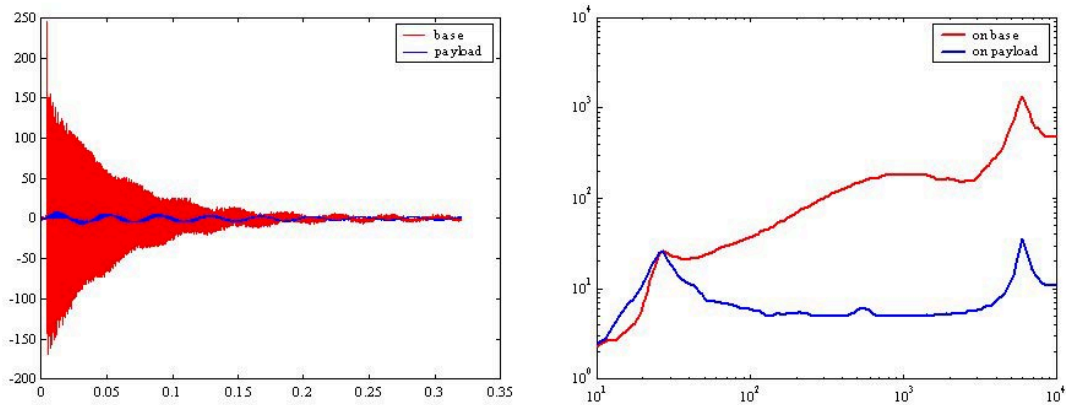


Figure 11 Component shock test data for JAWSAT SoftRide isolator

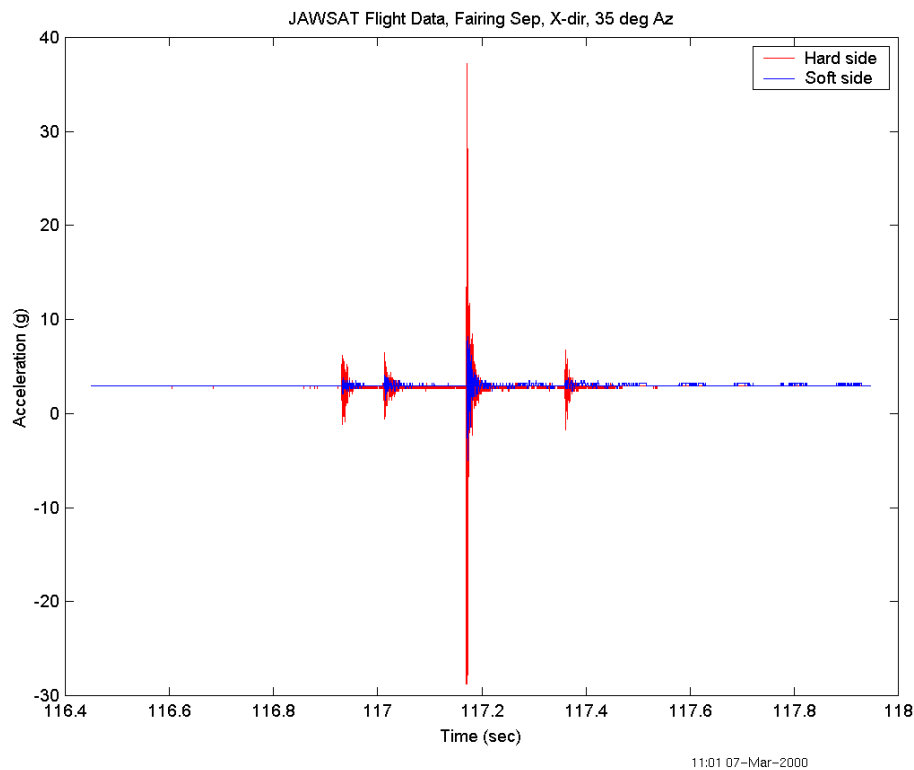


Figure 12 Fairing separation shock flight data showing SoftRide attenuation

## Conclusions

There is a need to reduce launch loads on spacecraft so that spacecraft and their instruments can be designed with more concentration on orbital performance rather than launch survival. A softer ride to orbit will allow more sensitive equipment to be included in missions, reduce risk of equipment or component failure, and possibly allow the mass of the spacecraft bus to be

reduced. These benefits apply to military as well as commercial spacecraft.

The SoftRide MultiFlex whole-spacecraft vibration isolation systems for both the Minotaur/JAWSAT and Minotaur/MightySat missions proved to be a very effective means of reducing spacecraft responses due to the broadband structure-born launch environment.



From both the coupled loads analyses and the flight data, it is clear that the SoftRide system performed very well to reduce structure-borne vibration levels transmitted to the spacecraft. The acceleration levels input to the spacecraft were reduced over a wide frequency range from about 30 Hz to 2000 Hz or more. Thus, the SoftRide isolation system served its main purpose of reducing low-frequency launch loads such as liftoff and stage ignitions as well as reducing higher-frequency shock and structure-borne acoustic loading.

The isolation system hardware design was elegant in its simplicity, which ultimately played a great part in its acceptance by both the spacecraft and launch vehicle manufacturers. This isolation system was simply inserted at an existing field joint. No flight hardware changes were required. The only change was to the guidance and control algorithms to account for bending frequency changes introduced by the isolation system. In the end, the choice to fly the isolation system proved to be a tremendous risk-reduction for the spacecraft by drastically increasing the spacecraft margins.

### **Acknowledgements**

This research and development was supported by a number of Small Business Innovative Research (SBIR) contracts from the Air Force Research Laboratory, Phillips Research Site along with funding from the Air Force Space and Missile Systems Center (SMC). Mr. Eugene Fosness and Dr. Dino Sciulli were the technical

monitors and Major Steve Buckley, SMC/TEB, was the driving force from SMC that made the first Minotaur flight possible. Their continued drive to fund and participate in research and development of whole-spacecraft isolation technology made the flights of the SoftRide system possible.

### **References**

1. Schoneman, S., Buckley, S., et. al, "Orbital Suborbital Program (OSP) "Minotaur" Space Launch Vehicle: Low Cost Space Lift For Small Satellites Using Surplus Minuteman Motors", AIAA Paper AIAA-2000-5068, AIAA Space 2000 Conference, September 19-21, 2000, Long Beach, CA.